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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(79)90646-4

DIRECT EVIDENCE FOR 3p–4h EXCITATIONS IN ^{15}N

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Received 3 April 1979

Direct comparison of data for $^{12}C(\alpha, p)^{15}N$ and $^{16}O(\alpha, p)^{19}F$ allows the identification of 3p–4h states in ^{15}N with $J = 5/2^+$, $9/2^+$ and $13/2^+$. Correspondence between ^{19}F and ^{15}N is very good, in both transfer strengths and excitation energies.

There has been a great deal of interest, both experimental [1–4] and theoretical [5,6] in the location of three-particle–four-hole (3p–4h) states in ^{15}N. We report here on their identification by a direct comparison of data for $^{12}C(\alpha, p)^{15}N$ and $^{16}O(\alpha, p)^{19}F$, obtained under almost identical experimental conditions.

In the $^{16}O(\alpha, p)^{19}F$ reaction [7] most of the transfer strength is concentrated in the $1/2^+$–$13/2^+$ members of the ground-state rotational band, with some splitting of the $11/2^+$ and $13/2^+$ strength. Apart from the splitting, this is just what one expects for three-nucleon transfer on a closed core leading to $(sd)^3$ states of the SU(3) classification $(\lambda\mu) = (60)$. Detailed shell-model calculations [8] are in accord with these results, including the splitting of the $11/2^+$ and $13/2^+$ transfer strengths.

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If the 3p–4h states of ^{15}N are relatively pure, we expect their strengths in $^{12}C(\alpha, p)$ to be the same as for the $(sd)^3$ cluster states in $^{16}O(\alpha, p)$, apart from kinematic and binding-energy effects. These effects should be accounted for by distorted-wave calculations.

A spectrum of the $^{12}C(\alpha, p)^{15}N$ reaction at a bombarding energy of 40.0 MeV and a laboratory angle of 15.6° is displayed in fig. 1. Strong states at 11.98 and 13.02 MeV are thought to be the $9/2^-$ and $11/2^-$ 2p–1h states and will not be discussed further. Our attention will be restricted to the strong positive-parity states . In the following discussion, we use the $9/2^+$ state as a reference since it is the highest-spin state of ^{19}F whose strength is not split.

A simple weak-coupling calculation, of the Basal–French–Zamick type [9,10], (using Zamick's parameters $a = 0.49$ MeV, $c = 0.50$ MeV), predicts the $9/2^+$ 3p–4h state in ^{15}N (of the form $^{19}F(9/2^+) \otimes {}^{12}C$ g.s.) to be at 10.81 MeV excitation. The 1p–2h $9/2^+$ state

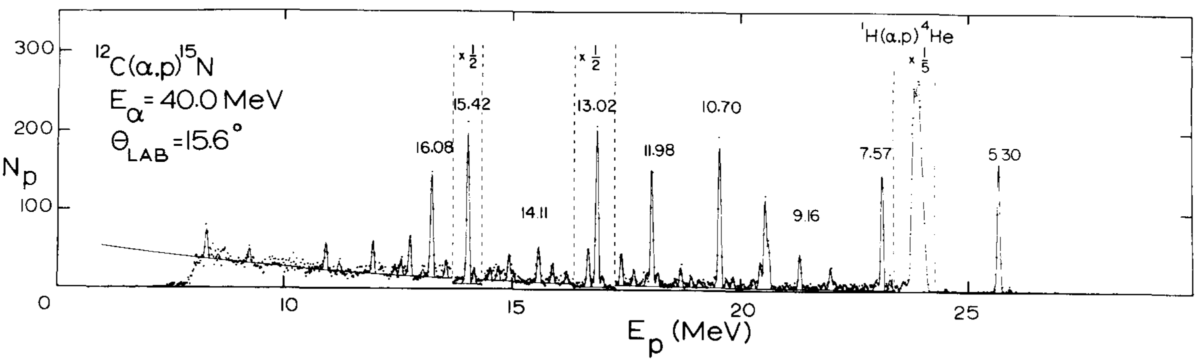

Fig. 1. Spectrum of the reaction $^{12}C(\alpha, p)^{15}N$ at a bombarding energy of 40 MeV and laboratory angle of 15.6°.

$(1d_{5/2} \otimes 2^+)$ should lie somewhat higher, near 12.5 MeV. These states will mix, but if the lower physical state is the constructive linear combination of the two, as is invariably the case, it will have most of the (α, p) strength. This is indeed what is observed. A $9/2^+$ state [11] at 10.70 MeV, which has been previously suggested to be mostly 3p–4h, is very strong in the $^{12}C(\alpha, p)$ spectrum. The strength of this state is twice that of the $9/2^+$ state in $^{16}O(\alpha, p)$. Virtually all of this factor of two arises from simple center-of-mass and binding energy effects and is accounted for by the DWBA calculations (see table 1).

In the weak-coupling model, the level spacings of 3p–4h states in ^{15}N are the same as those for 3p states in ^{19}F. Thus, if the $13/2^+$ strength is split in ^{15}N as it is in ^{19}F, we would expect two very strong $13/2^+$ levels near 12.5 and 18.3 MeV excitation in ^{15}N. This is not what is observed. But, the strongest state in the spectrum, at 15.42 MeV, lies roughly midway between these two energies. The 15.42 MeV level has previously been tentatively identified [1–4] as having $J^\pi = 13/2^+$ and was suggested to be predominantly of 3p–4h character. Its strength in $^{12}C(\alpha, p)$ is about 1.5 times that of the 4.65 MeV $13/2^+$ state in ^{19}F. If we compute the $13/2^+$ centroid in ^{19}F (weighing the excitation energies by the measured $^{16}O(\alpha, p)$ cross sections) it comes out as 7.26 MeV. We thus expect the $13/2^+$ state in ^{15}N (if it is not split) to lie 4.48 (= 7.26 − 2.78) MeV above the $9/2^+$, very close to where it is found.

The situation for the $5/2^+$ states is somewhat more complicated, since here the 1p–2h state should lie near 6 MeV, somewhat below the 3p–4h $5/2^+$ level expected near 8 MeV. Then, after mixing, the state that is predominantly 1p–2h can be the stronger of the two, merely because of coherence. In $^{12}C(\alpha, p)$ the $5/2^+$, $1/2^+$ levels [12] at 5.27 and 5.30 MeV are not resolved, but in $^{16}O(\alpha, p)$ the $5/2^+$ state is much stronger than the $1/2^+$ level. Furthermore, the shape of the combined ^{15}N angular distribution resembles more the one for $5/2^+$ than for $1/2^+$ in ^{19}F. It is thus likely that most of the 5.3 MeV peak in ^{15}N arises from the $5/2^+$ member. In fig. 2 we compare the combined

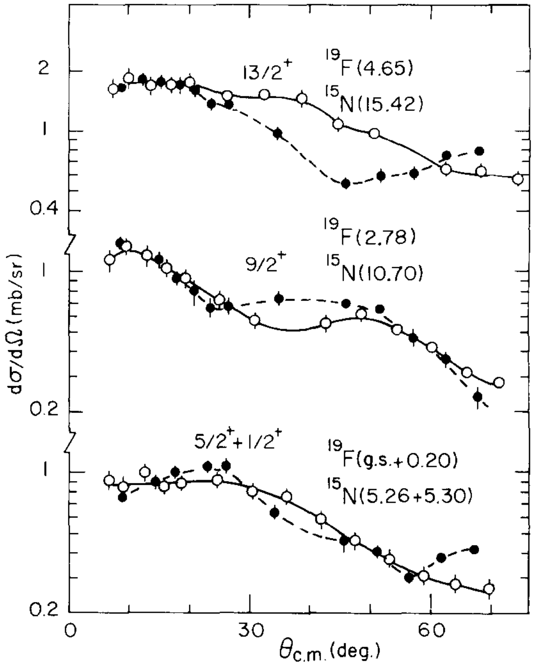

Fig. 2. Comparison of angular distributions for $^{12}C(\alpha, p)^{15}N$ (open circles) and $^{16}O(\alpha, p)^{19}F$ (closed circles) for final states with $J^\pi = 5/2^+$, $9/2^+$ and $13/2^+$. The lines serve only to connect the points.

Table 1
Excitation energies and (α, p) strengths for $5/2^+$, $9/2^+$ and $13/2^+$ states in ^{15}N and ^{19}F.

J^π	^{19}F		^{15}N		$\sigma(^{15}N)/\sigma(^{19}F)$	
	E_x (MeV)	Yield a)	E_x (MeV)	Yield a)	Exp.	DWBA b)
$5/2^+$	0.20	16	{ 5.26 9.16	42 14	2.6 c)	2.9
$9/2^+$	2.78	22	10.70	44	2.0	2.4
$13/2^+$	{ 4.65 10.42	46 38	15.42	86	1.0	1.7

a) Yield = $\int_{7°}^{70°} \sigma(A)\,dA$. b) Calculated with the optical model parameters of ref. [7].
c) After subtracting the 1p–2h contribution which is estimated to be 25% of the total.

$1/2^+$ and $5/2^+$ cross section in the two nuclei. Again the ^{15}N levels are about twice as strong as those in ^{19}F. However, here, we see also the second state, a $5/2^+$ at 9.16 MeV. Its cross section is only about 1/3 of the 5.3 MeV doublet (fig. 1), but this is still consistent with it being predominantly the 3p–4h $5/2^+$ state, as we see below.

If we write

$$\psi(5.27; 5/2^+) = \alpha(1\text{p}-2\text{h}) + \beta(3\text{p}-4\text{h}) ,$$

and

$$\psi(9.16; 5/2^+) = \beta(1\text{p}-2\text{h}) - \alpha(3\text{p}-4\text{h}) ,$$

then our data require $\beta^2 \approx 1/4$, $\alpha^2 \approx 3/4$. This gives the factor-of-three difference in cross section for the two states, if $(\text{sd})^3$ transfer is about three times as strong as $(\text{sd})(1\text{p})^2$ transfer, which is quite reasonable. If we then use these coefficients to compute the centroid of the 3p–4h component, we get 8.19 MeV, in very good agreement with its expected position of 2.58 MeV below the $9/2^+$ level. Seventy-five percent 1p–2h component for the 5.27 MeV state is consistent with data from ^{14}C(d, n) [13], which measures a spectroscopic factor of 0.75.

Our results are summarized for the $5/2^+$, $9/2^+$ and $13/2^+$ states in fig. 3. For $13/2^+$, the strength is split in ^{19}F, but apparently not in ^{15}N, whereas the $5/2^+$ strength is split in ^{15}N but not in ^{19}F. The $5/2^+$ splitting is easily understood as outlined above. The $13/2^+$ splitting in ^{19}F is predicted by shell-model calculations, but in ^{15}N all the $13/2^+$ transfer strength appears to reside in a single state.

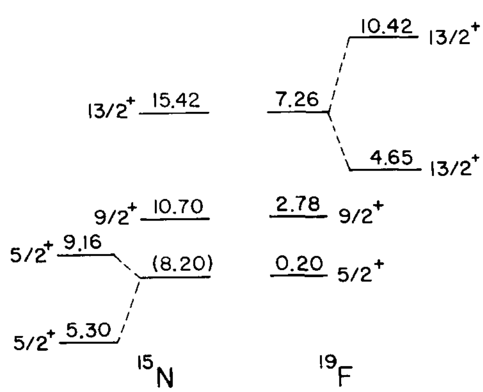

Fig. 3. Excitation energies of 3p states in ^{19}F and 3p–4h states in ^{15}N.

The present experiment does not allow any definite conclusions concerning other 3p–4h states. The $1/2^+$ state at 5.26 MeV could contain an appreciable fraction of the 3p–4h configuration. But the fact that $1/2^+$ states are weak in (α, p), coupled with the close spacing of the 5.3 MeV doublet, prohibits a quantitative analysis. It is perhaps of interest that known $1/2^+$ states at excitation energies of 8.31 and 9.05 MeV have yields too small to be detectable.

Concerning $3/2^+$ states, the one at 7.30 MeV excitation is predominantly a 1p–2h state from its strength [14] in ^{14}N(d, p). Two $3/2^+$ states at 8.57 and 9.93 MeV have approximately equal (α, p) strengths and their combined yield is such as to suggest them as candidates for the 3p–4h $3/2^+$ state. Their centroid is at 9.25 MeV, very close to the expected position of 9.47 MeV.

The $7/2^+$ state at 7.57 MeV has near unity spectroscopic factor [14] in ^{14}N(d, p) and hence is predominantly 1p–2h. The $7/2^+$ 3p–4h level should lie near 13.39 MeV. No $7/2^+$ states are known in this region, but the only nearby state with sufficient strength to be the 3p–4h $7/2^+$ is the level at 13.18 MeV, which has unknown spin. It is thus a candidate for the 3p–4h $7/2^+$ level.

The lowest $11/2^+$ state in ^{19}F is at 7.95 MeV. Thus, if the $11/2^+$ splitting is the same in ^{15}N, we expect the 3p–4h $11/2^+$ state near 15.87 MeV. There is a strong state at 16.08 MeV that has the appropriate strength, but again its J^π is unknown.

In summary, direct comparison of data for the reactions ^{16}O(α, p) and ^{12}C(α, p) displays explicitly the 3p–4h excitations in ^{15}N for states with $J^\pi = 5/2^+$, $9/2^+$ and $13/2^+$. The $9/2^+$ and $13/2^+$ states appear to be relatively pure in ^{15}N, but the $5/2^+$ configuration is split among two states at 5.26 and 9.16 MeV. It is the upper of the two that has a dominant 3p–4h component, though it has a smaller cross section. Centroids of states with $J^\pi = 5/2^+, 9/2^+$, and $13/2^+$ in ^{15}N are shown to be within about 80 keV of their positions in ^{19}F.

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